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Non-thermal leptogenesis and baryon asymmetry in different neutrino mass models

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Abstract

In the present work we study non-thermal leptogenesis and baryon asymmetry in the universe in different neutrino mass models discussed recently. For each model we obtain a formula relating the reheating temperature after inflation to the inflaton mass. It is shown that all but four cases are excluded and that in the cases which survive the inflaton mass and the reheating temperature after inflation are bounded from below and from above.

1. Introduction

The Standard Model (SM) of particle physics (for a review on the subject see e.g. [1]) is a very successful theoretical framework for all low-energy phenomena. However, it is widely considered to be a low-energy limit of some underline fundamental theory. Perhaps the most direct evidence for physics beyond the SM is the recent discovery that neutrinos have small but finite masses [2–4]. A simple and natural way to explain the tiny neutrino masses is via the seesaw mechanism [5]. According to that, the existence of super-heavy right-handed neutrinos is postulated and the smallness of the masses of the usual SM neutrinos is due to the largeness of the masses of the new neutrinos. Solar, atmospheric, reactor and accelerator neutrino experiments (for a summary of three-flavour neutrino oscillation parameters see e.g. [6]) seem to indicate neutrino masses in the sub-eV range ($0.001 < m_\nu < 0.1$ eV), which implies that heavy right-handed neutrinos weigh $\sim 10^{10}$–10^{15} GeV [7].

On the other hand, the baryon asymmetry in the universe (BAU) is one of the most challenging problems for modern cosmology. Both Big-Bang nucleosynthesis [8] and CMB data (for example from WMAP [9]) show that in the universe one baryon corresponds approximately to one billion photons. This very small number should be computable in the framework of the theory of the elementary particles and their interactions we know today. Nowadays, the most popular way to obtain the BAU is through leptogenesis (for an incomplete list see e.g. [10] and for a review see [11]). Initially a lepton asymmetry is generated through the out-of-equilibrium decays of right-handed neutrinos and then the lepton asymmetry is partially converted to baryon asymmetry through the non-perturbative "sphaleron" effects [12]. In general leptogenesis can be thermal or non-thermal. Thermal leptogenesis usually requires very high reheating temperature after inflation [13]. This can be problematic because of the gravitino constraint. In supersymmetric models (for reviews in supersymmetry see e.g. [14] and for supersymmetry in cosmology see e.g. [15]) with spontaneous supersymmetry breaking the superpartner of the graviton, the gravitino, gets a mass depending on how the supersymmetry is broken. In gravity mediated supersymmetry breaking the gravitino mass is in the range $m_{3/2} = 100$ GeV–1 TeV and the gravitino (if not the lightest supersymmetric particle) is unstable with a lifetime larger than Nucleosynthesis time $t_N \sim 1$ s and dangerous for cosmology. This gravitino problem [16] can be avoided provided that the reheating temperature after inflation is bounded from above in a certain way, namely $T_R \leqslant (10^6$–$10^7)$ GeV [17].

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Table 1
Predicted values of the solar and atmospheric neutrino mass-squared differences and three mixing parameters (from [20])

Type	Δm^2_{21} [10^{-5} eV^2]	Δm^2_{23} [10^{-3} eV^2]	$\tan^2\theta_{12}$	$\sin^2 2\theta_{23}$	$\sin\theta_{13}$
DegT1A	8.80	2.83	0.98	1.0	0.0
DegT1B	7.91	2.50	0.27	1.0	0.0
DegT1C	7.91	2.50	0.27	1.0	0.0
InvT2A	8.36	2.50	0.44	1.0	0.0
InvT2B	9.30	2.50	0.98	1.0	0.0
NHT3	9.04	3.01	0.55	0.98	0.074

Therefore one can see that heavy right-handed neutrinos can have important implications both for particle physics and cosmology. Various neutrino mass models [18,19] have been proposed and their predictions on neutrino masses and mixings have been studied thoroughly. The requirement for the right baryon asymmetry in the universe as well as for the right phenomenology for light neutrino masses and mixings puts severe constraints on right-handed neutrinos. Recently six concrete neutrino mass models were discussed and a comparison of numerical predictions on baryon asymmetry for these models was presented [20]. Two of the models were almost consistent with the observed BAU, while the rest of them predicted either a small ($\eta \leqslant 10^{-19}$) or a large ($\eta \geqslant 10^{-6}$) baryon asymmetry. The analysis was performed in the framework of thermal leptogenesis. The aim of the present work is to study the same models in the framework of non-thermal leptogenesis and derive the constraints on the inflaton mass and the reheating temperature after inflation.

Our Letter is organized as follows. After this introduction we review the six neutrino mass models and lepton asymmetry in Section 2 and we discuss non-thermal leptogenesis for these models in Section 3. Our results are presented in Section 4 and we conclude in Section 5.

2. Review of the different neutrino mass models and of lepton asymmetry

Here we give a brief review of the six neutrino mass models [19] discussed recently in [20]. The interested reader can find more details in [19,20]. In particular, all the information about the models are collected in Appendix A of [20]. There is one normal hierarchical model (NHT3), two inverted hierarchical models (InvT2A, InvT2B) and three degenerate models (DegT1A, DegT1B, DegT1C). According to seesaw mechanism, the light left-handed neutrino mass matrix m_ν, the heavy right-handed neutrino mass matrix M_R and the Dirac neutrino mass matrix m_D are related as follows

$$m_\nu = m_D M_R^{-1} m_D^T, \tag{1}$$

where M_R^{-1} is the inverse of M_R and m_D^T is the transpose of m_D. The predicted values of the neutrino mass-squared differences and mixing parameters are shown in Table 1.

In thermal leptogenesis for the SM case the BAU $\eta \equiv n_B/n_\gamma = 6.1 \times 10^{-10}$ is computed by the formula [20]

$$\eta = 0.0216\kappa\epsilon, \tag{2}$$

where κ is the dilution factor and ϵ is the CP asymmetry. The dilution factor is not needed for our discussion in non-thermal leptogenesis scenario. However we remark in passing that it is determined by numerical integration of Boltzmann equations and that it can be estimated by analytical expressions given in [21].

On the other hand, the CP asymmetry is a basic quantity for our presentation and we shall now discuss its relation to the neutrino mass matrices. The lepton asymmetry in the universe is generated by CP violating out-of-equilibrium decay of the heavy neutrinos $N \to lH^*$ and $N \to \bar{l}H$. The CP asymmetry ϵ is defined as

$$\epsilon = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \tag{3}$$

with $\Gamma = \Gamma(N \to lH^*)$ and $\bar{\Gamma} = \Gamma(N \to \bar{l}H)$ the decay rates. It is given by the interference between tree-level and one-loop decay amplitudes and it is found to be [22]

$$\epsilon = \frac{1}{8\pi (Y_\nu Y_\nu^\dagger)_{11}} \sum_{j=2,3} \mathrm{Im}\big[\big(Y_\nu Y_\nu^\dagger\big)^2_{1j}\big] \times \big(f\big(M^2_{R_j}/M^2_{R_1}\big) + 2g\big(M^2_{R_j}/M^2_{R_1}\big)\big), \tag{4}$$

where the two functions $f(x)$, $g(x)$ have the form

$$f(x) = \sqrt{x}\big[1 - (1+x)\ln(1+1/x)\big], \tag{5}$$

$$g(x) = \frac{\sqrt{x}}{2(1-x)}. \tag{6}$$

Both functions behave like $\sim -1/(2\sqrt{x})$ for $x \gg 1$. In this approximation the asymmetry ϵ takes the form

$$\epsilon = -\frac{3}{8\pi (Y_\nu Y_\nu^\dagger)_{11}} \sum_{j=2,3} \mathrm{Im}\big[\big(Y_\nu Y_\nu^\dagger\big)^2_{1j}\big] \frac{M_{R_1}}{M_{R_j}}. \tag{7}$$

Finally, using the seesaw formula ϵ becomes [23]

$$\epsilon = \frac{3 M_{R_1} m_{\nu_3} \delta_{\mathrm{eff}}}{16\pi v^2}, \tag{8}$$

where v is the Higgs vev and δ_{eff} is the CP-violating phase. However, in the quasi-degenerate spectrum $M_{R_1} \simeq M_{R_2} < M_{R_3}$ the CP asymmetry is enhanced by a factor given by [24]

$$R = \frac{M_{R_1}}{2(M_{R_2} - M_{R_1})}. \tag{9}$$

The three right-handed neutrino masses for each model are shown in Table 2 while the CP asymmetry and baryon asymmetry are shown in Table 3. The Dirac neutrino mass matrix

Table 2
The three right-handed Majorana neutrino masses in GeV (from [20])

Type	Case (i): $\|M_j\|$	Case (ii): $\|M_j\|$
DegT1A	$4.28 \times 10^9, 1.16 \times 10^{10}, 3.84 \times 10^{13}$	$3.47 \times 10^7, 9.42 \times 10^7, 3.81 \times 10^{13}$
DegT1B	$4.05 \times 10^7, 6.16 \times 10^{11}, 7.6 \times 10^{13}$	$3.28 \times 10^5, 4.98 \times 10^9, 7.6 \times 10^{13}$
DegT1C	$4.05 \times 10^7, 6.69 \times 10^{12}, 6.99 \times 10^{12}$	$3.28 \times 10^5, 4.85 \times 10^{11}, 7.81 \times 10^{11}$
InvT2A	$3.28 \times 10^8, 9.70 \times 10^{12}, 6.79 \times 10^{16}$	$2.64 \times 10^6, 7.92 \times 10^{10}, 6.70 \times 10^{16}$
InvT2B	$5.6527 \times 10^{10}, 5.6532 \times 10^{10}, 5.38 \times 10^{16}$	$4.5971 \times 10^8, 4.5974 \times 10^8, 5.34 \times 10^{16}$
NHT3	$6.51 \times 10^{10}, 7.97 \times 10^{11}, 1.01 \times 10^{15}$	$5.27 \times 10^8, 6.45 \times 10^9, 1.01 \times 10^{15}$

Table 3
Calculation of CP asymmetry ϵ and baryon asymmetry η for each neutrino mass model (from [20])

Type	Case (i): ϵ	Case (ii): ϵ	Case (i): η	Case (ii): η
DegT1A	2.10×10^{-6}	1.71×10^{-8}	4.99×10^{-9}	4.06×10^{-11}
DegT1B	2.66×10^{-18}	2.16×10^{-20}	1.60×10^{-23}	1.30×10^{-25}
DegT1C	1.74×10^{-18}	1.69×10^{-20}	1.05×10^{-23}	1.02×10^{-25}
InvT2A	1.59×10^{-14}	1.27×10^{-16}	9.94×10^{-19}	7.96×10^{-21}
InvT2B	1.47×10^{-2}	1.62×10^{-4}	5.40×10^{-5}	5.94×10^{-7}
NHT3	5.90×10^{-7}	4.78×10^{-9}	2.17×10^{-9}	1.76×10^{-11}

m_D can be either the charged lepton mass matrix m_l (case (i)) or the up-quark mass matrix m_u (case (ii)). We see that NHT3 and DegT1A models are almost consistent with the observed BAU, while the rest of the models lead either to very small baryon asymmetry, $\eta \leqslant 10^{-19}$ (DegT1B, DegT1C, InvT2A), or to large baryon asymmetry, $\eta \geqslant 10^{-6}$ (InvT2B).

3. Non-thermal leptogenesis

In the non-thermal leptogenesis scenario [25] the heavy neutrinos are produced through the direct non-thermal decay of the inflaton. We start by introducing three heavy right-handed neutrinos (one for each family) N_i, $i = 1, 2, 3$, with masses $M_{R_1}, M_{R_2}, M_{R_3}$. They interact with the inflaton through Yukawa couplings with λ_i the coupling constants for this type of interaction. We assume that after the slow-roll phase of inflation the inflaton decays predominantly into the heavy neutrinos. With a Yukawa coupling between the inflaton and the heavy neutrinos, the inflaton decay rate Γ_ϕ is given by

$$\Gamma_\phi \equiv \Gamma(\phi \to N_i N_i) = \frac{1}{4\pi} |\lambda_i|^2 M_I, \tag{10}$$

where M_I is the inflaton mass. The reheating temperature after inflation T_R (defined by $H(T_R) = \Gamma_\phi$, with H the Hubble parameter) is given by

$$T_R = \left(\frac{45}{4\pi^3 g_*}\right)^{1/4} (\Gamma_\phi M_{\mathrm{pl}})^{1/2}, \tag{11}$$

where M_{pl} is Planck mass and g_* is the effective number of relativistic degrees of freedom at the reheating temperature. For the reheating temperatures that we shall consider all the particles are relativistic and for MSSM $g_* = 915/4 = 228.75$, while for SM $g_* = 427/4 = 106.75$.

Any lepton asymmetry $Y_L \equiv n_L/s$ produced before the electroweak phase transition is partially converted into a baryon asymmetry $Y_B \equiv n_B/s$ via sphaleron effects [12]. The resulting Y_B is

$$Y_B = C Y_L \tag{12}$$

with the fraction C computed to be $C = -8/15$ in the MSSM and $C = -28/79$ in the SM [26]. The lepton asymmetry, in turn, is generated by the CP-violating out-of-equilibrium decays of the heavy neutrino

$$N_1 \to l H^*, \qquad N_1 \to \bar{l} H. \tag{13}$$

In the framework of non-thermal leptogenesis the lepton asymmetry can be obtained by a simple formula [11]

$$Y_L = \frac{3}{2} BR(\phi \to N_1 N_1) \frac{T_R}{M_I} \epsilon, \tag{14}$$

where BR is the branching ratio for the decay of the inflaton to the lightest heavy right-handed neutrino. Following the fourth paper in [25] we shall consider that $M_1 \geqslant 100 T_R$, because in that case the neutrino N_1 is always out of thermal equilibrium. The decay $\phi \to N_1 N_1$ is kinematically allowed provided that

$$M_I > 2M_1. \tag{15}$$

We will assume that $BR \approx 1$, that is the inflaton decays practically only to the lightest of the right-handed neutrinos. This is possible even if the inflaton is heavy enough to decay to all right-handed neutrinos as long as $|\lambda_1|^2 \gg |\lambda_2|^2, |\lambda_3|^2$. Combining the above formulae we obtain

$$Y_B = C Y_L = C \frac{3}{2} \frac{T_R}{M_I} \epsilon \tag{16}$$

or

$$T_R = \left(\frac{2 Y_B}{3 C \epsilon}\right) M_I. \tag{17}$$

From the WMAP data [9] we know that

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6.1 \times 10^{-10}. \tag{18}$$

If we recall that the entropy density for relativistic degrees of freedom is $s = h_{\mathrm{eff}} \frac{2\pi^2}{45} T^3$ and that the number density for photons is $n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$, one easily obtains for today that $s = 7.04 n_\gamma$. Thus for Y_B we have

$$Y_B = 8.7 \times 10^{-11}. \tag{19}$$

Finally we recall that $M_I > 2M_1$ and $M_1 \geqslant 100 T_R$.

4. Results

Now we can present our results. We shall begin with the SM case first and we shall use for the fraction C the SM value, namely $C = -28/79$. For each neutrino model (12 cases in total) the CP asymmetry ϵ as well as the right-handed neutrino mass M_1 are known. Therefore we have (i) a formula relating the reheating temperature to the inflaton mass, (ii) a lower bound for the inflaton mass $M_I > 2M_1$, and (iii) an upper bound for the reheating temperature $T_R \leqslant 0.01 M_1$. Furthermore, using the relationship between T_R and M_I we are able to convert the upper limit for T_R to a corresponding upper limit for M_I and also the lower limit for M_I to a corresponding lower limit for T_R. So both T_R and M_I are bounded both from above and from below. Let $T_R^{\min}$ and $T_R^{\max}$ be the lower and higher value for the reheating temperature respectively. Then $T_R^{\min} < T_R \leqslant T_R^{\max}$ and obviously it is required that $T_R^{\max} > T_R^{\min}$, which is not satisfied for all cases. In fact most of the cases are excluded. The only cases for which the constraint is satisfied are:

- DegT1A, case (i), for which:

$$8.56 \times 10^9 < M_I \leqslant 5.49 \times 10^{11}\ \mathrm{GeV}, \tag{20}$$
$$6.67 \times 10^5 < T_R \leqslant 4.28 \times 10^7\ \mathrm{GeV}; \tag{21}$$

- NHT3, case (i), for which:

$$1.3 \times 10^{11} < M_I \leqslant 2.35 \times 10^{12}\ \mathrm{GeV}, \tag{22}$$
$$3.6 \times 10^7 < T_R \leqslant 6.51 \times 10^8\ \mathrm{GeV}; \tag{23}$$

- InvT2B, case (i), for which:

$$1.13 \times 10^{11} < M_I \leqslant 5.09 \times 10^{16}\ \mathrm{GeV}, \tag{24}$$
$$1.25 \times 10^3 < T_R \leqslant 5.65 \times 10^8\ \mathrm{GeV}; \tag{25}$$

- InvT2B, case (ii), for which:

$$9.2 \times 10^8 < M_I \leqslant 4.55 \times 10^{12}\ \mathrm{GeV}, \tag{26}$$
$$9.29 \times 10^2 < T_R \leqslant 4.6 \times 10^6\ \mathrm{GeV}. \tag{27}$$

One can see from the results presented above that inflationary models in which $M_I \sim 10^{13}$ GeV, like e.g. chaotic [27] or natural [28] inflation, are compatible only with one neutrino model (InvT2B, case (i)). Furthermore, for a concrete inflationary model with a given inflaton mass our results allow us to know what the reheating temperature must be and also what the inflaton decay rate Γ_ϕ is and what the inflaton Yukawa coupling $|\lambda_1|$ is. For example, in chaotic or natural inflation we obtain

$$M_I \sim 10^{13}\ \mathrm{GeV}, \tag{28}$$
$$T_R \sim 10^5\ \mathrm{GeV}, \tag{29}$$
$$\Gamma_\phi \sim 10^{-8}\ \mathrm{GeV}, \tag{30}$$
$$|\lambda_1| \sim 10^{-10}. \tag{31}$$

On the other hand, if some day it turns out that for example model NHT3 is the correct one for neutrino masses, then we have a prediction for the inflaton mass, $M_I \sim (10^{11}\text{–}10^{12})$ GeV. In that case all inflationary models that predict a different inflaton mass are ruled-out.

At this point we should add a comment regarding the gravitino constraint. In supersymmetric models one has to address the gravitino problem. Adding supersymmetry the expression for the baryon asymmetry will change slightly by a numerical factor of order one. Therefore one could use the results obtained so far for the non-supersymmetric case. If we require that $T_R \leqslant (10^6\text{–}10^7)$ GeV then we see that the models InvT2B and DegT1A are already compatible with the gravitino constraint, the model NHT3 is marginally compatible (for the lower values for T_R) with the gravitino constraint and finally the model InvT2B can be made compatible with the gravitino constraint lowering the upper bound for T_R

$$1.25 \times 10^3 < T_R \leqslant \left(10^6\text{–}10^7\right)\ \mathrm{GeV}. \tag{32}$$

5. Conclusions

In the present work we have studied non-thermal leptogenesis in six neutrino mass models proposed earlier and discussed recently in the literature. For each model we have obtained a formula relating the inflaton mass M_I to the reheating temperature after inflation T_R. In fact according to this formula T_R is proportional to M_I. Hence, the bigger the inflaton mass the bigger the reheating temperature. In a concrete inflationary model (chaotic [27], natural [28], supersymmetric hybrid [29], etc.) with a given mass for the inflaton, the right baryon asymmetry implies a certain reheating temperature after inflation. This in turn implies a certain decay rate for the inflaton field and a certain value for the inflaton Yukawa coupling. Furthermore, kinematical reasons and the requirement for non-thermal leptogenesis lead to a lower and an upper bound both for M_I and T_R. Our results show that in most of the neutrino models under study the lower bound is not compatible with the upper bound and therefore only four cases survive. If we also take into account the gravitino constraint $T_R \leqslant (10^6\text{–}10^7)$ GeV, then in one of these cases the reheating temperature is even more constrained.

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